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Life cycle assessment of greenhouse gas mitigation of production and use of bio-methane

Sensitivity of effects from N_2O emissions

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Life cycle assessment of greenhouse gas mitigation of production and use of bio-methane: sensitivity of effects from N_2O emissions

Keywords: Biogas / bio-methane, technological process chain, LCA & optimization, N2O, climate protection potential

ABSTRACT: Biogas and bio-methane that are based on energy crops are renewable energy carriers and therefore potentially contribute to climate protection. However, significant greenhouse gas emissions resulting from agricultural production processes must be considered. Among those, the production and use of fertilizer, and the resulting leaching of nitrous oxide (N2O) are crucial factors.
This paper provides an integrated life cycle assessment (LCA) of biogas (i.e. bio-methane that has been upgraded and injected into the natural gas grid), taking into account the processes of fermentation, upgrading and injection to the grid for two different types of biogas plants. The analysis is based on different feedstocks from crop rotation systems for different locations in Germany. A special focus is on the sensitivity of assumptions on nitrous oxide emissions on overall greenhouse gas emissions.
Much research exists on the measurement or modeling of the actual N2O emissions that result from farming processes. Since there is as yet no precise regional data, most analyses use tier-1 data from the IPCC national greenhouse gas inventories as a default. The present paper coincides with recent research in indicating that this data varies at the regional level. However, it is not the scope of the article to evaluate the quality of existing data for N2O emissions, but to show the effects of different assumptions to the life cycle assessment of greenhouse gases from bio-methane. Thus, a link between the provision of emission data and the practical implementation of biogas technology is provided.
The main result is that the supply chain of substrates from agricultural processes appears to contribute the most to the greenhouse gas emissions of bio-methane. The "worst case" scenario where 5% of the nitrogen fertilizer used is emitted in form of N2O shows that the greenhouse gas mitigation potential of bio-methane versus natural gas is very small, so there is not much margin for error in the plant technology.

1 INTRODUCTION

Biogas is produced through fermentation of wet biomass. Unlike most European countries, most plants in Germany use energy crops from dedicated farming as a feedstock, rather than residues or sewage gas.
Since late 2006 several projects for injection of upgraded biogas into the natural gas grid have been set up. The aim is to use the existing infrastructure to distribute the bio-methane to a larger number of end users. Bio-methane –defined as raw biogas after upgrading - as a perfect substitute for natural gas can thus be used in combined heat and power (CHP) applications as well as for provision of domestic heat or as an alternative vehicle propellant.
Considering the process of upgrading, injection and distribution to different end users, the biogas industry has moved forward from the local, small-scale "on-site" energy supply model to new mar-

kets and possibilities. However there is still debate as to what role bio-methane can play as a regional, agricultural energy carrier, and as to its climate impact.
The author provides an integrated life cycle assessment (LCA) of biogas (respectively bio-methane after upgrading and injection into the natural gas grid), taking into account two different types of biogas plants: (1) the current state-of-the-art as an industrialized, but average efficient biogas plant in the year 2008 (labeled as "state of the art") and (2) a new, large-scale plant with optimized technology, representing already the next generation of biogas plants by widely exploiting the optimization potential of the near future (labeled as "optimized technology"). The focus is thus on large biogas plants (≥ 1 000 Nm^3/h); the given results do not, therefore, hold in any case for small-scale, agricultural biogas plants. The two different types of plants and the specific technical features are outlined in the following section 2.

Already, several studies regarding the overall GHG emissions and LCA of biogas or bio-methane based on energy crops exist (e.g. [1], [2], [3], [4]) have been published. As has been shown [5], comparison of the results is rather difficult as the LCA depends strongly on the feedstock used, the technology applied and the assumptions taken for the agricultural and technical aspects. As well, the functional unit as well as the system boundaries vary. Thus, the relevant assumptions for the presented analysis are laid out in this paper.

The analysis is not only based on system engineering, but also on different feedstock provided in crop rotation systems for different locations in Germany. The focus of this paper is, however, to analyze the effects from different assumptions regarding nitrous oxide emissions to the climate protection potential of bio-methane, produced in different configurations of plants. The results of the sensitivity analysis regarding the assumptions on nitrous oxide emissions and the effects to the LCA are presented in section 5.

2 TECHNOLOGICAL PROCESS CHAIN: BIO-METHANE

The technological process chain of bio-methane is pictured in the following scheme. Simplified, the process chain can be divided into four steps: (1) provision of substrates, (2) fermentation to biogas through anaerobic digestion, (3) upgrading of the raw gas to the same quality as natural gas, (4) handling of digestates. The provision of the energy needed for the operation of the reactor and the upgrading unit can be seen as a fifth step. In all process steps greenhouse gas (GHG) emissions can evolve: directly through leakage of methane, or indirectly through the use of fossil energy or agricultural processes.

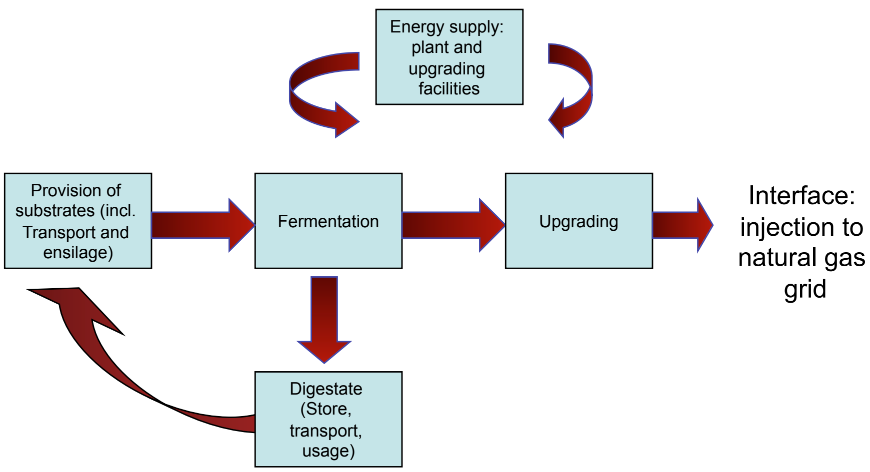

Figure 1: scheme of process chain bio-methane

The four process steps will be briefly described in the next paragraphs. The input data to the LCA for both plant configuration types as resulting from the description is listed in Table 1.

(1) **Provision of substrates:**
This step includes the cultivation and harvest of the energy crops as well as the ensilage. Illustrative, maize will be taken as a reference crop, while the full LCA has been made for five different crop rotation systems. Most relevant are the data on N-P-K-fertilizers, lime, pesticide and diesel used in machinery. This data has been provided by [6] and represents the actual situation on five different locations in Germany.
Furthermore, emissions of nitrous oxide from microbial processes in the soil have been taken into account to the amount of 1 % of the deployed nitrogen fertilizer [7]. This assumption and the given effect will be examined closer in section 5 of this paper.
During ensilage of substrates material losses between 5 and 15 % occur, according to [8]. Those numbers have been chosen as maximum and minimum value for the two plant configuration types.

(2) **Fermentation**:
In the reactor itself there can be leakage of methane due to not properly sealed elements, diffusion from gas-bearing parts or process disturbances. The exact amount of leakage is not exactly scientifically assessed yet, so there is the need for further examination and the quality of data is less than for the other figures. In accordance with previous studies (as in [9] and [2]) a number of 1 % of the methane production has been applied. As long as accurate measurements have not been done it is assumed that emissions will be halved for the optimum case presented in the optimized technology.
Another important parameter is the yield of crude biogas that can be achieved during the digestion. It depends a lot on the constitution and quality of substrate, but also on the construction of the reactor itself. So far, for maize as reference crop, for the calculation a value of 200 m^3 per ton of fresh mass (tFM) has been used [10], but operating experience from plant operators show, that even today 10 – 20 % more can be achieved.

(3) **Handling of digestates:**
As mentioned before the LCA is done for large-scale professional operated plants, so it is assumed that the storage of digestate is fully covered and no methane leakage will occur at this point. Nevertheless, in the sensitivity analysis the effects of a not completely covered storage will be explored to give a perspective of the importance of this section.
The digestate will be returned to the cultivaton of the crops and deployed as fertilizer. The nutrients are not decomposed during the digestion and phosphate and potassium can be fully regained. Between 50 – 70 % of nitrogen in the digestate are plant available and can substitute mineral nitrogen fertilizer [11].

(4) **Upgrading:**
The Pressure Swing Adsorption (PSA) is chosen as an example for upgrading technologies to be depicted for this article. Highly relevant is the slip rate of methane, which is about 2% with most PSA procedures [12]. As there is a regulation of methane slip since the beginning of 2009 in Germany [13], currently it is the common method to put a burner after the PSA to convert the methane catalytically or thermal to carbon dioxide. Again, for both plant configuration types a methane slip following the after treatment of 0.01% is assumed.

(5) **Energy supply:**
For the operation of the biogas plant and the upgrading facilities energy is needed in form of heat for the reactor and electricity for the stirring unit and pumps. The PSA needs electrical and thermal energy, as well. The data is taken from [12] and from the plan operator.

Table 1: Input data for the LCA for the plant configuration types: state of the art and optimized technology

			State of the art	optimized Technology
supply with substrates*	diesel use	l/ha	82.9	82.9
	N-fertilizer	kg/ha	141.75	141.75
	material loss ensilage	% mass	**15**	**5**
	N2O emissions (soil)	%**	1	1
fermentation	CH4 leakage reactor	Vol %	**1**	**0.5**
	yield of raw gas	m3 / t FM	**200**	**220**
handling of digestate	CH4 leakage store	%	0	0
	subsitution of N-fertilizer (mineral)	%	70	70
	subsitution of P,K-fertilizer (mineral)	%	100	100
up-grading	CH4 slip (no aftertreatment)	%	2	2
	CH4 slip (aftertreatment applied)	%	0.01	0.01
energy supply	electricity (reactor)	kWh el/ t FM	36	36
	heat (reactor)	kWh th/ t FM	83	83
	electricity (PSA)	kWh el/m3 BG	0.3	0.3
	heat (PSA)	kWh th/m3 BG	0	0

***exemplay for maize, without accounting of digestate**
**** calculated in % of nitrogen fertilizer deployed**

3 GREENHOUSE GAS EMISSIONS FACTORS OF BIO-METHANE

Two different types of biogas plants have been in the focus of the study: the current state of the art as well as a new, large-scale plant as an optimum case ("optimized technology"). The input parameter for both vary regarding the material loss in ensilage, the yield of raw gas achieved and the methane leakage from the reactor as can be taken from Table 1. As the focus in this section is on the effects of plant technology and the differences between the two plant configurations only maize is taken as feedstock.

Figure 1 shows the results of the LCA for the GHG emission factors of both plants and the sensitivity analysis. Both plants are operated in a professional way; nevertheless the difference between both types is clearly visible (figure 2). Compared to the state of the art plant, GHG emissions can be decreased by about 30% with optimized technology mostly through better yield of raw gas and less methane leakage. It is obvious that the provision of substrates is the main factor for GHG emissions once the plant operating technology is optimized. It should be examined further for optimization. Emissions occur mostly due to the use of energy for the production of farming utilities as fertilizer, pesticide etc. and the use of fuel in machinery.

The results of the thus calculated LCA were opposed to the overall emissions of natural gas. Assuming that bio-methane as a perfect substitute can be used in any way as natural gas, the climate protection potential of bio-methane can in one approach be seen as the difference between the GHG intensities of both energy carriers. The emissions for the exploration, transportation and energetically use of natural gas, according to [14] sum up to about 230 g CO_2eq/kWh (illustrated through the red line in Figure 3).

In order to categorize emissions from the process, it can be stated that about 25 % of emissions from the provision of substrate is due to nitrous oxide from soil processes (as will be further explained in the next section). Thus, about one fifth of the overall emissions are nitrous oxide, another 12- 17 % are methane from leakage. The biggest part therefore is still carbon dioxide emissions.

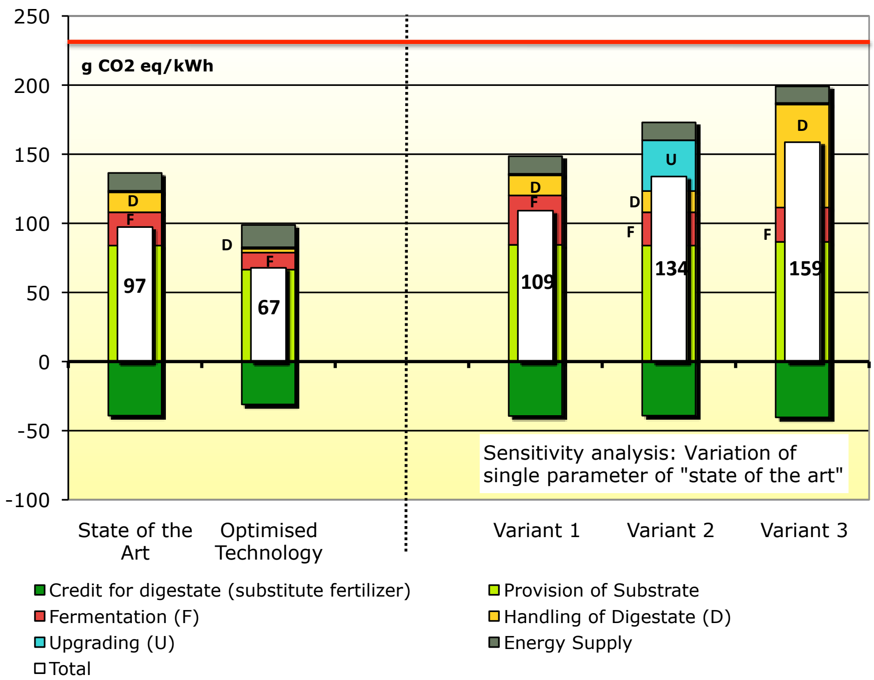

Figure 2: GHG factors of the process chain bio-methane: sensitivity analysis.
Variant 1: increased methane leakage in reactor (1.5% instead of 1%); Variant 2: increased methane slip in PSA (no after treatment, slip of 2% instead of 0.01%); Variant 3: digestate storage not completely covered – moderate emissions of 2.5% of gas stored. Red line: GHG emissions of natural gas

4 PROVISION OF SUBSTRATES – ADJUSTED CROP ROTATION SYSTEMS

In cooperation with agricultural experts [6], for five different locations throughout Germany (Dornburg, Gülzow, Güterfelde, Ascha, Soest) regionally adjusted crop rotation systems for the provision of biogas substrates were composed. They all contain maize as the most advantageous energy crop due to the high yield of raw gas as well as the high agricultural yield per acreage, but they all contain different crops as well, as they are typical and well known in the specific regions. For the LCA only the crops are considered that are used exclusively for biogas production. The substrates from a location are digested together as a mixture in the fermenter. Table 2 shows the feedstock mix from each location.

Table 2: Composition of biogas substrates at the five locations

	Maize	Rye	Sorghum	Triticale	Grass*	Barley
Dornburg	x	x	x			
Gülzow	x	x		x		
Güterfelde	x	x	x			
Ascha	x	x			x	
Soest	x		x			x

* mixture of hairy vetch (vicia villosa), crimson clover (trifolium incarnátum) and Italian ryegrass (lolium multiflorum)

The approach was not so much to not use maize, but to use not only maize, in order to contribute to a more diversified agriculture. So, a combined cultivation of rye and sorghum is applied in Güterfelde on a rather dry location and in Dornburg while in the Soest and Gülzow two different kinds of whole-crop silage were calculated. In Ascha a mixture of the grasses hairy vetch (vicia villosa), crimson clover (trifolium incarnátum) and Italian ryegrass (lolium multiflorum) was tested. The results of all substrate mixtures processed in a plant according to the "optimized technology" are shown in Figure 3.

The columns for "cultivation" include the use of diesel for drilling, maintenance and harvest as well as the application of pesticide and fertilizer (potassium, phosphate, nitrogen, magnesium, lime). As nitrous oxide emissions are in the focus of this article they are depicted separately. In "plant technology" the emissions from the reactor itself, the upgrading unit and from the energy supplied are summarized.

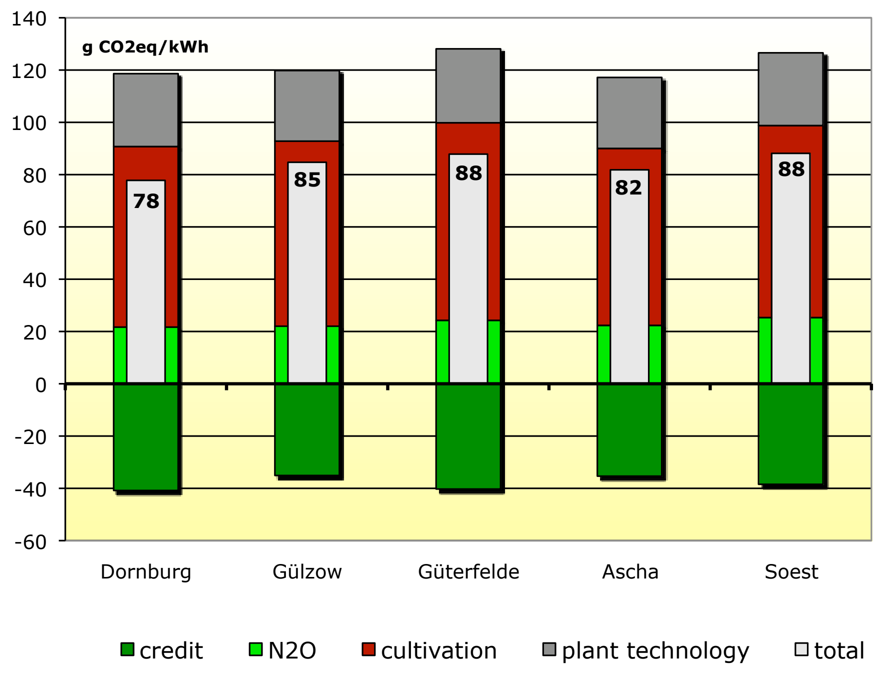

Figure 3: GHG balance of bio-methane from different substrates in regionally adjusted crop rotation systems

As can be seen from the results as shown in Figure 3, the difference between the five locations varies only between 78 g CO_2eq/kWh (Dornburg) and 88 g CO_2eq/kWh (Güterfelde and Soest) if optimized technology is applied and the credit for use of digestate instead of mineral fertilizer is taken into account. Doing so is well in line with the current state of the art, as both plant operator as crop cultivator benefit from the substitution of mineral fertilizer because it increases the ecological benefit and reduces the necessary expenses.
The given results for the five locations have to be compared to 67 g CO_2eq/kWh that result from the use of maize as the only feedstock in plants according to optimized technology, when average data for the supply of maize is used.

One aim of the examination was to prove that there are other choices than just maize as substrate that still can result in acceptable GHG balances. So there is no need to plant maize in large-scale monocropping farms, which is strongly not recommended from an biodiversity, ecological and even agricultural point of view as mono cropping may allow pest and rodents to spread and is not in line with good agricultural praxis.

Another aim was to get away from average data for whole Germany and base the LCA on data collected from real situations and locations, which provide a good overview about the different regions in Germany. Thus, a bandwidth of locations was chosen regarding for different typical soil qualities and weather conditions.

5 EFFECTS OF NITROUS OXIDE EMISSIONS TO THE CLIMATE PROTECTION POTENTIAL OF BIO-METHANE

Nitrous oxide emissions are not the most important factor in the overall GHG balances but they still play a role. In the above described examinations and results a value of 1 % of deployed nitrogen fertilizer was assumed following the IPCC national GHG inventories [7]. A lot of recent international research [16] indicates, however, that this data might be much too low. [17] indicated, that this factor of 1 % should be multiplied by 3 or even 5, while on the other hand preliminary test with nitrification inhibitors show, that at least for some German locations the N_2O emissions could be halved to 0.5 % [18], [19]. Aside from that there are critical voices [20] claiming the percentaged approach is not useful as local soil and weather specification have an important impact.

Given this partly controversial discussion the question remains: What are realistic GHG emission factors for the production and use of biogas from agricultural feedstock and how large are the resulting GHG reduction potentials? Thus, the author cannot contribute to solving the discussion regarding whether it should be 1 or 5 %; instead it is the aim of this paper to show in how much the different values for N_2O emissions effect the overall climate protection potential of biogas.

Therefore in a sensitivity analysis values from 0.5% to 5% were calculated in the plant according to the current state of the art. It has to be noted that different approaches are used: IPCC [7] is not following a complete life cycle approach but the tier-1 factor in general has been derived to attribute emissions to a certain "polluter". So the 1% quoted refer to direct plot emissions of the fertilizer deployed. They apply to any substitute fertilizer but also to the digestate. In a rough estimation "indirect" emissions were assumed to be an additional 0.5%, summing up to 1.5 %. The results from

these emission factors and the “best case” assumption according to [18; 19] as input to the LCA are depicted in the three columns on the left hand side of the diagram.
On the other hand the 3 – 5 % N_2O emissions according to [17] refer to freshly fixed reactive nitrogen only, assuming that the conversion from nitrogen to nitrous oxide has to be accounted for only once in the whole life cycle. Therefore no additional N_2O is emitted from the digestate, leading to an increased credit for the usage as substitute for mineral fertilizer.
The results are again compared to the overall emissions of natural gas as explained in section 3.

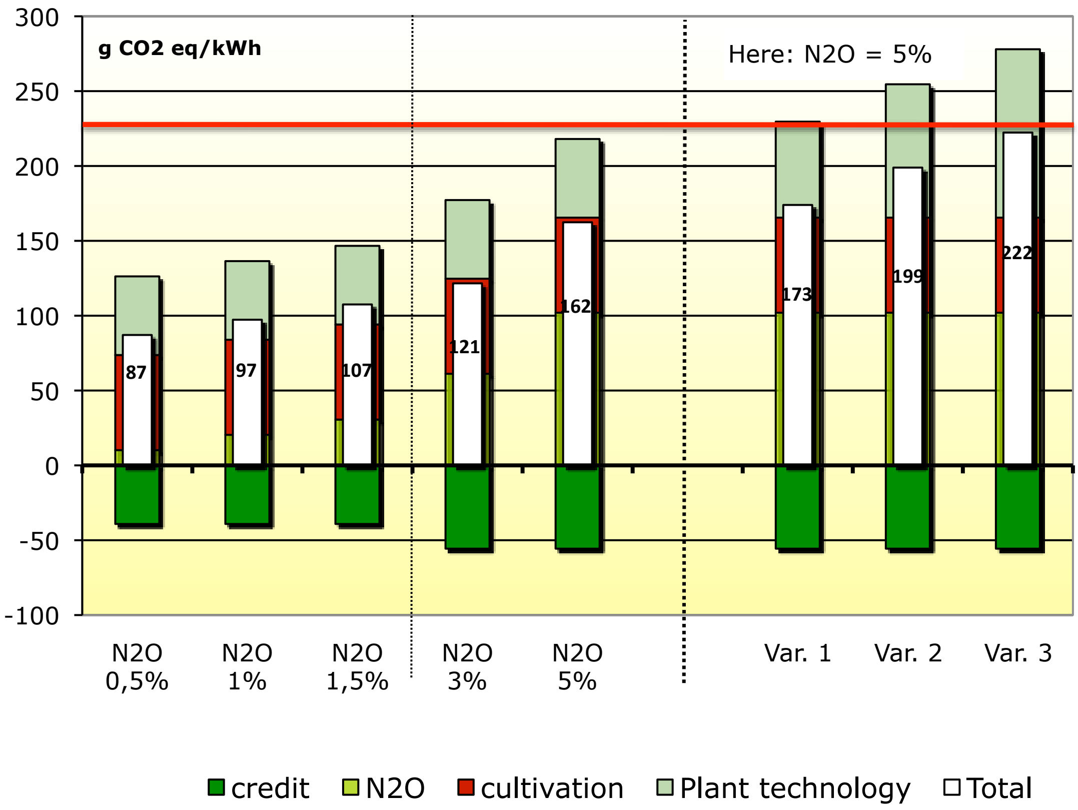

Figure 4: Sensitivity analysis: effects of different assumptions of N_2O emissions to the overall GHG balance in the state-of-the-art biogas plant
Variant 1: increased methane leakage in reactor (1.5% instead of 1%); Variant 2: increased methane slip in PSA (no after treatment, slip of 2% instead of 0.01%); Variant 3: digestate storage not completely covered – moderate emissions of 2.5% of gas stored; Red line: GHG emissions of natural gas

It is obvious, that the climate protection potential of bio-methane is the highest, the lower the assumed N_2O emissions are. The first four columns are for the biogas plant of state of the art today, as described before. If the digestate is used as fertilizer, as it is customary in Germany, there is still a remaining climate protection potential, even if the nitrous oxide emissions rise to 5 %. However, bio-methane is far from being an energy carrier with “no climate impact”.

If as a “worst case” taken from the current discussion, a data of 5 % of deployed nitrogen fertilizer is emitted as nitrous oxide, this means for the production of bio-methane, technology of the current state of the art is just good enough to keep the advantage above natural gas. Technology of lesser standards as to higher emissions will produce bio-methane with higher GHG intensity, as the three columns on the right side of figure 3 show. Depicted are the same variants as in figure 2, only assuming N_2O emissions of 5 % of the deployed nitrogen fertilizer.

The climate protection potential is alarmingly shrinking. If there are methane leakage only to the amount of 2,5% from the digestate storage it is not possible to reduce GHG emissions by using bio-methane instead of natural gas. If the credit of digestate for mineral fertilizer would not used - which is rather unlikely – the GHG balance is even higher that for the fossil energy carrier.

6 CONCLUSIONS

Two different types of biogas plant configurations have been closely examined and analyzed: a plant according to the state of the art and one deploying the currently most optimized technology. The results of the LCA do not hold in any case for small-scale plants that might not be not equally professional operated.
Once the technology is optimized to the point of only small methane leakage from the reactor, a considerable yield of raw gas from the substrates and most importantly a closed storage for digestate, the cultivation of substrates contributes to the biggest amount to greenhouse gas emissions of the whole process chain.
The most GHG gases of the production of bio-methane are still carbon dioxide emissions but methane from direct leakage and nitrous oxide from microbial processes play a role, as well.
Bio-methane can be produced from energy crops from dedicated farming without harming or negatively effecting the environment if regionally adjusted crop rotation systems are deployed. Aside from maize, there are various crops that result in nearly the same GHG balances - so there is no need for monocropping of maize.
The current controversy discussed matter of nitrous oxide emissions from organic processes can be of high importance to the overall GHG balance of bio-methane. Analysis shows that if the "worst case" of 5 % of deployed nitrogen fertilizer has to be assumed, there is not much margin of error for the plant technology. If the current state of the art technology is deployed for example even minor leakage of methane from the digestate storage can diminish the GHG difference of bio-methane to natural gas to nearly zero, thus annihilating the climate protection potential of the energy carrier.

ACKNOWLEDGEMENTS

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